Development of high-power laser ablation process for polycrystalline diamond polishing Part 2: upscaling of PCD ultra-short pulsed laser ablation to high power

Scalbert, William, Tanner, David, Holtz, Ronald

William Scalbert, David Tanner, Ronald Holtz, "Development of high-power laser ablation process for polycrystalline diamond polishing Part 2: upscaling of PCD ultra-short pulsed laser ablation to high power," Proc. SPIE 11273, High-Power Laser Materials Processing: Applications, Diagnostics, and Systems IX, 1127303 (2 March 2020); doi: 10.1117/12.2544963

SPIE.

Event: SPIE LASE, 2020, San Francisco, California, United States

Development of high-power laser ablation process for polycrystalline diamond polishing: Part 2. Upscaling of ultra-short pulsed laser ablation to high power

William Scalbert*[a, b], David Tanner[b], Ronald Holtz[c]
[a]Element Six Ltd, Shannon Airport, Shannon, Co. Clare, Ireland; [b]School of Engineering, Bernal Institute, University of Limerick, Limerick, Co. Limerick, Ireland; [c]Class 4 Laser Professionals AG, Industriering 43, Lyss, Switzerland

ABSTRACT

Properties of diamond are extreme. Since the first successful synthesis of diamond in 1955, the use of synthetic diamond has widely spread into diverse industries (e.g. manufacturing, electronics and optics). However, being the hardest material known, the manufacture of diamond material into an engineered tool is extremely challenging. The polishing process remains a traditional mechanical method existing for over hundreds of years. The development of alternative ways of polishing diamond is an active subject of research and has recently been investigated in topics such as chemically assisted mechanical polishing or ion beam polishing. Laser polishing is another alternative and a state-of-the-art laser polishing method is presented in this paper. A high-power femtosecond laser ablation process is developed to achieve a high throughput polishing process of polycrystalline diamond composite (PCD) wafers. Laser ablation trials are carried out with a femtosecond laser delivering over 80W average power on three different PCD grades synthesized by high-pressure/high-temperature. The role of the fluence is highlighted and the effect of the burst mode on PCD is demonstrated for the first time to the best of our knowledge. Eventually, the roughness of the initial surface on fine grain diamond material is reduced by two while the ablation rate is twice higher than the removal rate achieved by mechanical polishing.

Keywords: Ultra-short pulse laser, high-power laser, femtosecond laser, laser polishing, polycrystalline diamond, synthetic diamond

***william.scalbert@e6.com; phone +353 (0) 87 700 8216; www.e6.com; www.ul.ie**

1. INTRODUCTION

1.1 Feasibility study at low power

Polishing diamond is done mechanically using a diamond resin bonded wheel rotated at high speed. This costly process generates high thermal stress within the polycrystalline diamond composite (PCD) material induced from the friction between diamond grit in the wheel and the surface of the PCD wafer resulting in important processing defects (including cracks and chipping)[1,2,3]. As detailed previously, a laser process is developed as an alternative to this mechanical process, the advantages being a lower processing cost and less thermal defects[4]. Feasibility studies were carried out with a low power industrial laser which reached a maximum average power of 5W. The maximum ablation rate achieved across every PCD grade was 31% lower than the removal rate of the conventional mechanical polishing process. The PCD material was supplied by Element Six and the different tested grades are defined according to Table 1.

High-Power Laser Materials Processing: Applications, Diagnostics, and Systems IX, edited by Stefan Kaierle, Stefan W. Heinemann, Proc. of SPIE Vol. 11273, 1127303 · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2544963

Table 1. Specifications of the PCD grades used for the laser ablation trials

PCD Grades	Average Grain Size (µm)	Diamond Content (wt%)	Cobalt Content (wt%)
Fine diamond grain	1	80	20
Medium diamond grain	12	90	10
Coarse diamond grain	30	90	10

Such low laser ablation performance does not justify the optimization of the laser application with a low power laser. However, these experiments allow the establishment of fundamental relationships between the process parameters and the ablation rate/surface roughness. Mainly, a higher average power output from the laser increases the ablation rate and the highest ablation rate for every set average power of the laser is reached for an optimal fluence which varies depending on the PCD grade (Figure 1a). Furthermore, a lower pulse duration results in higher surface quality (Figure 1b). At the lowest pulse duration of 230fs, most processed surfaces (at 1W, 3W,4W and 5W) present a lower surface roughness Sa than before pulse laser ablation (PLA).

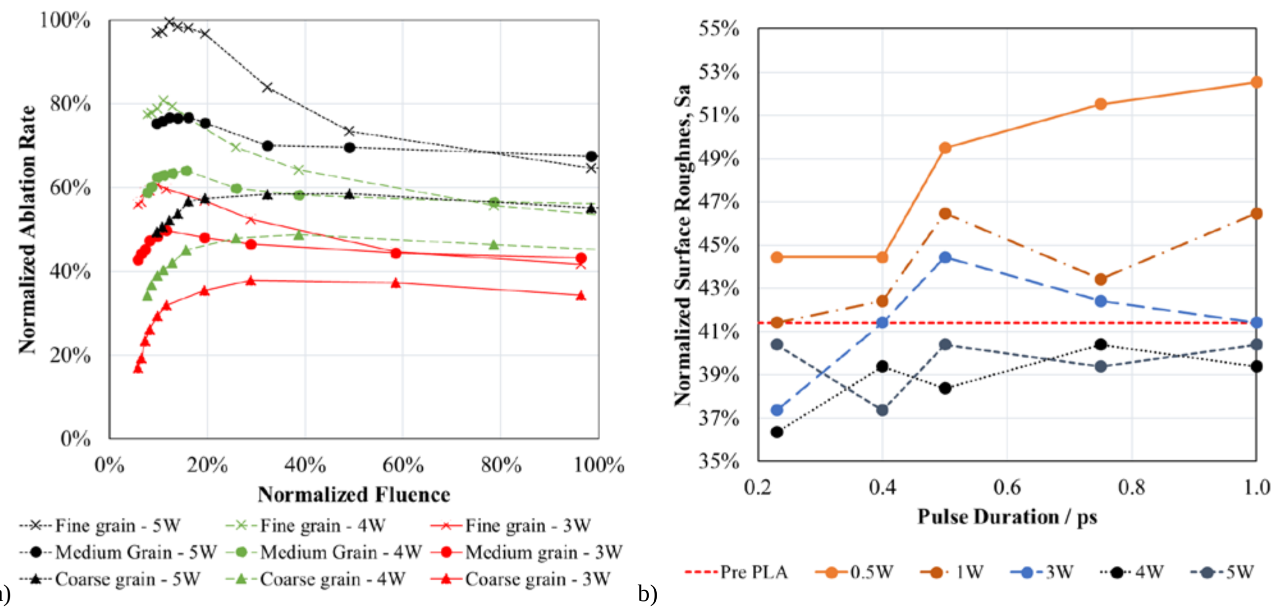


Figure 1. a) Variation of the ablation rate with the fluence at three different average powers for fine, medium and coarse diamond grains - b) Variation of roughness (Sa) on fine diamond grain surface with the pulse duration at different average powers, the initial surface roughness pre-PLA is indicated.

1.2 Process optimization at high power

These fundamental studies indicate that a high-throughput laser polishing process could be developed using a high-power laser with ultra-short pulse duration. Following these feasibility results, a laser reaching 80W of average power with a minimum pulse duration of 350fs equipped with a pulse burst mode is developed and this paper presents the optimization work carried out with this newly developed high-power ultrafast laser system for diamond polishing. The objective of this optimization work presented here is to produce the lowest surface roughness attainable while achieving a higher removal rate than mechanical polishing. Strategies to reduce the surface roughness are studied on three PCD grades (small grain, medium grain and coarse grain sizes). The impact of the increase of power from 5W to 80W on the heat accumulation effects[5] as well as the role of the number of scanning passes[6] and the fluence on the surface roughness[7] are investigated in this paper. Finally, data in literature indicates the benefits of the burst mode for metal processing[8,9]. The implementation of this burst mode appears to always result in higher performances of the laser ablation process.

After an extensive literature review, it appears that the results presented in this paper for the implementation of burst mode for PCD materials laser processing are novel.

2. EXPERIMENTAL SET-UP

2.1 Laser ablation trials set-up

The laser ablation trials are undertaken with an industrial high-power ultra-short pulse laser. A maximum average power of 80W is measured on the workpiece with an Ophir powermeter model Orion. Table 2 lists the manufacturer's specifications for the low power laser used for the previous feasibility studies and the high-power laser utilized here.

Table 2. Laser source specifications

Laser specifications	Low power laser	High power laser
Wavelength	1030nm	1030nm
Pulse length	230fs – 10ps	350fs – 10ps
Maximum average power	5W	100W
Frequency	60kHz – 1MHz	330kHz – 2MHz
Polarization	Linear	Linear
M^2 (beam quality factor)	<1.2	>1

A beam expansion system from Jenoptik is fitted on the beam path of the laser, which is capable of expanding the laser beam diameter by up to 4 times. Combined with this, a quarter wave plate in included to polarize the beam circularly (polarization effects are not studied here). The scanning system is a galvoscanner set with a telecentric focal lens. The workpieces, (PCD wafers) stand on conventional CNC stages (X, Y, Z) to allow linear movements for successive ablation trials and for positioning of the PCD top surface in focus. The schematic of the final experimental set up is represented in Figure 2:

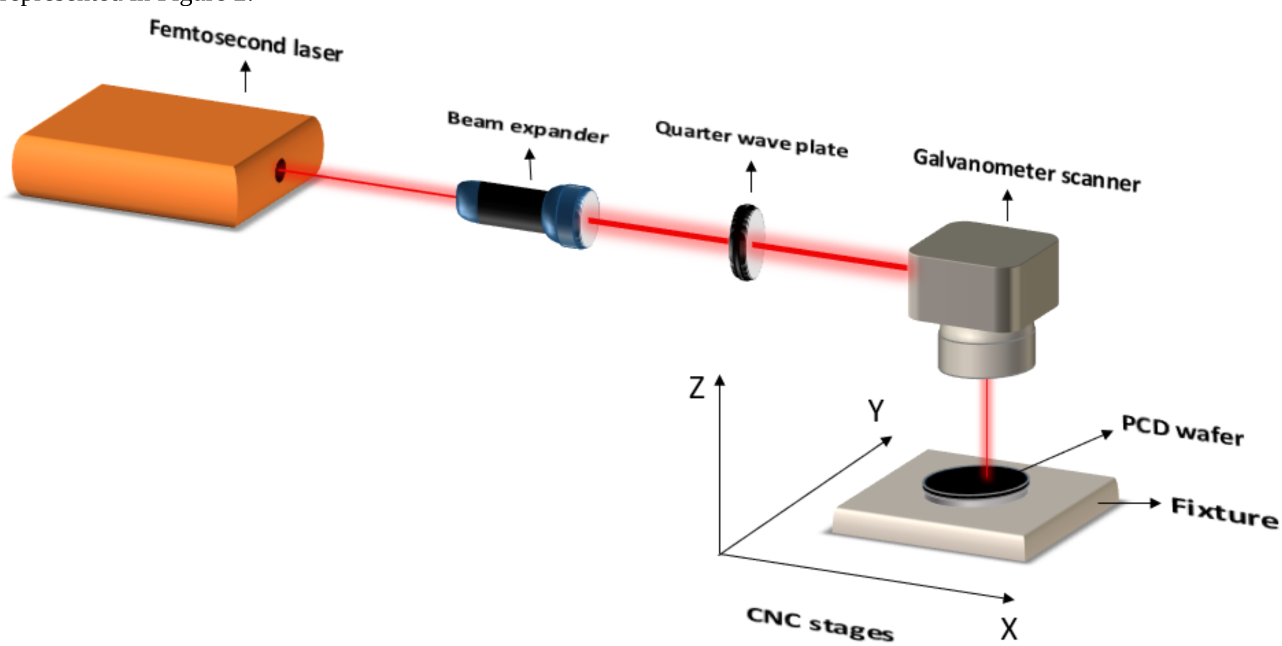
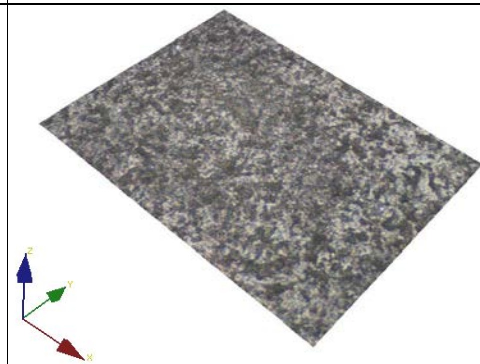
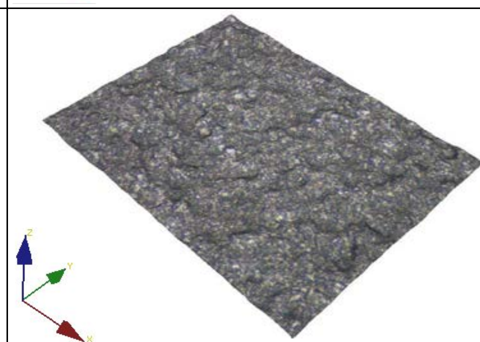
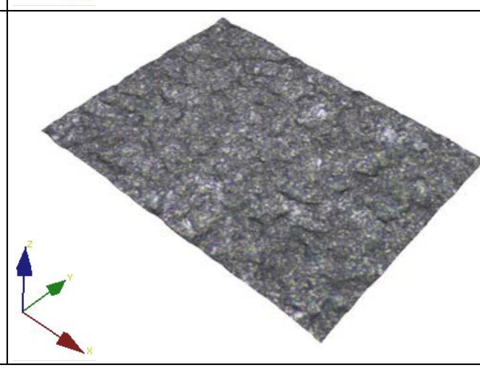


Figure 2. Schematic of the laser system used for testing

The ablation trials consist of ablating 6mm x 6mm squares into PCD wafers with various diamond grain sizes and compositions as outlined in Table 1. The PCD wafer surfaces are initially lapped before the pulsed laser ablation trials. The initial surface roughness is measured per PCD grade. Table 3 lists the initial surface roughness measured by 3D laser scanning microscopy along with microscopy images for the three processed PCD grades.

Table 3. Initial surface roughness values Sa and Sz with the corresponding microscopy images of the lapped surfaces pre-PLA per PCD grades. The images represent an area of 285µm x 216µm

PCD Grade	Sa (µm)	Sz (µm)	Microscopy images
Fine diamond grain	0.41	5.02	
Medium diamond grain	0.47	4.67	
Coarse diamond grain	0.44	5.53	

During an ablation trial, the PCD wafer is observed to heat up. To prevent the PCD wafer temperature from having an influence on the next ablation trial, the wafer is cooled down on a granite table to ambient temperature between successive trials. No stage movement in the Z axis direction is included to ensure that the focal position is maintained during the ablation process and the focal position of the laser beam is set on the top surface of the wafer; therefore, the defocusing effect is constant for every square.

During the duration of the trials, the pulse duration is fixed at 350fs, the minimum value, as the lowest pulse duration gives highest ablation rate and best surface finish (Figure 1b)[4,10,11]. The influence of the overlap is studied to extend the results from 5W to 80W and to determine the overlap threshold at 80W before having critical heat accumulation and significant damage on the surface[5,6]. At fixed laser parameters (power/fluence), the beam overlap is modified by adjusting the hatching distance and the scanning speed. The number of scanning passes over the surface is observed to also have an impact on the surface roughness. The surface is scanned with the same scanning/laser parameters for different number of passes to determine the optimal number of scanning passes where the surface roughness is the lowest. The variation of the surface roughness with the fluence is first measured for single pulse processing (one burst). The frequency is changed from 330kHz up to 2MHz to modify the fluence at a fixed average power of 80W and a fixed beam overlap of 67%, below the expected heat accumulation, by adjusting the scanning speed and the external modulator to select the number of pulses. Then, these trials are repeated with a burst mode varying from 2 to 6 to observe the variation between single pulse and burst mode processing.

2.2 Measurement set-up

The area roughness parameters Sa and Sz are reported to characterize the surface roughness: the arithmetical average Sa is a conventional roughness parameter in the industry and Sz is additional one as a complementary parameter to describe the maximum damage caused by PLA. They are measured by 3D laser scanning microscopy with a Keyence VKX. Five measurements are taken per sample (four in the corners and one in the middle of the squares) and averaged to minimize the standard deviation up a maximum value of 5% and 7% for Sa and Sz respectively across all the trials. Images of the surfaces are taken by confocal microscopy with an Alicona G4 (mag x50). Every image represents an area of 285µm x 216µm.

3. PROCESSING STRATEGIES TO REDUCE PCD SURFACE ROUGHNESS

3.1 Optimal overlap and number of passes

A high beam overlap causes significant damage due to heat accumulation[5,6]. Heat accumulation is observed to occur over a 95% beam overlap at an average power of 5W on fine diamond grain[1]. At 80W and a fluence of 12%, Figure 3a shows that, over an 87% beam overlap, Sa and Sz rise which means the appearance of significant surface defects resulting from heat accumulation. Indeed high unevenness of the surface with deep craters can be observed in Figure 3b corresponding to the ablated surface with a 97% beam overlap. Whereas the surface is more homogeneous and even in Figure 3c representing the surface ablated with an 84% beam overlap. Even though, the fluence was 90% lower due to a 3.5 times larger spot size compared to the trials at 5W, the heat accumulation occurs at a lower beam overlap threshold of 87%. During subsequent experiments, the beam overlap is set lower than 85% to prevent significant surface damage at 80W.

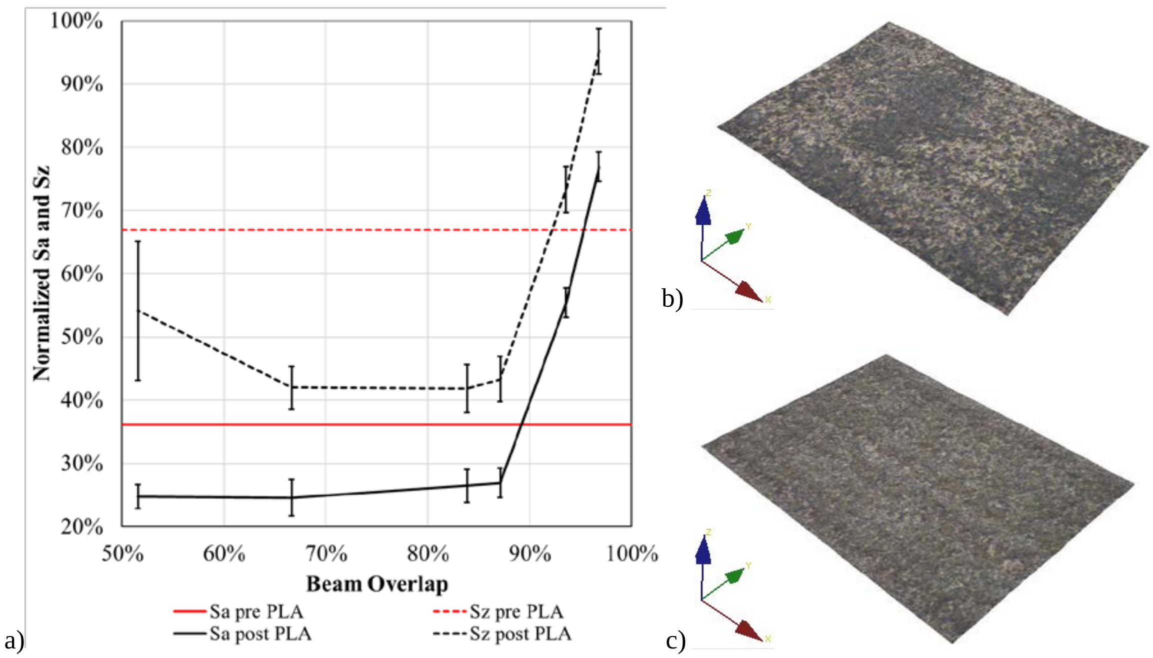


Figure 3. Variation of roughness (Sa and Sz) in function of the beam overlap on fine diamond grain surface, the initial surface roughness pre-PLA is indicated (a). Microscopy images of the surfaces ablated with a beam overlap of 97% (b) and 84% (c).

Figure 4a indicates that 20 passes is optimal to ensure the highest quality surface roughness. The Sa reduces when the number of passes increases, however the Sz has an opposite trend. 20 scanning passes appears to be the value where Sa and Sz are simultaneously the lowest. More passes allow the laser beam to reduce the average roughness until a limit, but it also amplifies the formation of cavities as observed in Figure 4b compared to Figure 4c. These cavities are created from the residual heat accumulated passes after passes.

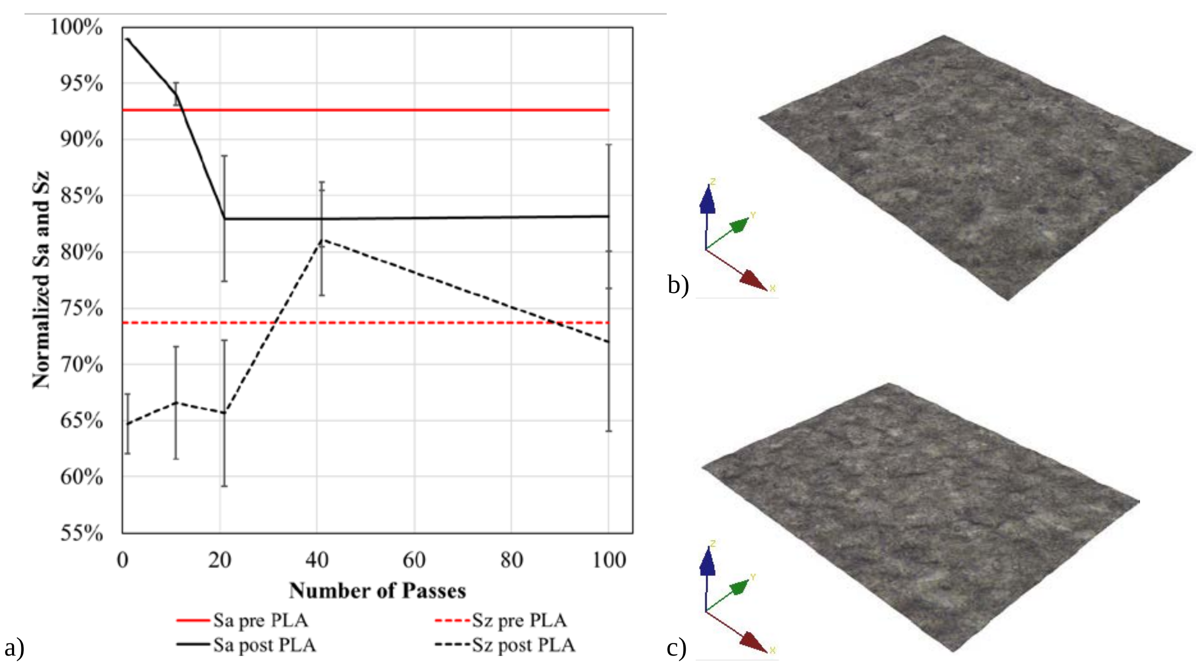


Figure 4. Variation of roughness (Sa and Sz) in function of the number of passes on coarse diamond grain surface (a) with microscopy images of the surfaces ablated with scanning passes of 20 (b) and 100 (c). The initial surface roughness pre-PLA is indicated.

3.2 Influence of the fluence

The trials from section 3.1 allow to set the beam overlap to 67% and number of scanning passes to 20 to optimize the ablation process. Fine and medium grain diamond surfaces are ablated with different values of fluence. The results displayed in Figure 5 show that the diamond surfaces behave differently to the fluence depending on the grain size. The surface roughness of the medium diamond grain samples reduces with the fluence: Sa and Sz decreases with the fluence until a limit at high fluence. Unfortunately, it is not possible to confirm the trend at higher values of fluence due to the limitation in average power of the laser source. However, the surface roughness of fine grain diamond reaches the lowest values for an optimal range of fluence around 50% (the Sz in Figure 5b suddenly becomes very low at the highest fluence, the result can be questioned due to the measurement error). Additionally, the capability to smoothen the surface by laser differs between the two grades. It appears that medium grain surfaces are more challenging to smoothen than fine-grained ones. Indeed, the fine grained surfaces are smoother compared to pre-PLA surfaces after laser processing for a wide range of fluence while medium grained surfaces are barely smoothened at high fluence compared to pre-PLA surface: high fluence, over 65%, is required to ablate medium grain without deterioration (increase of surface roughness) of the initial roughness whereas only 50% fluence reduces the initial roughness of fine diamond grain by a factor 1.6 (Figure 5a).

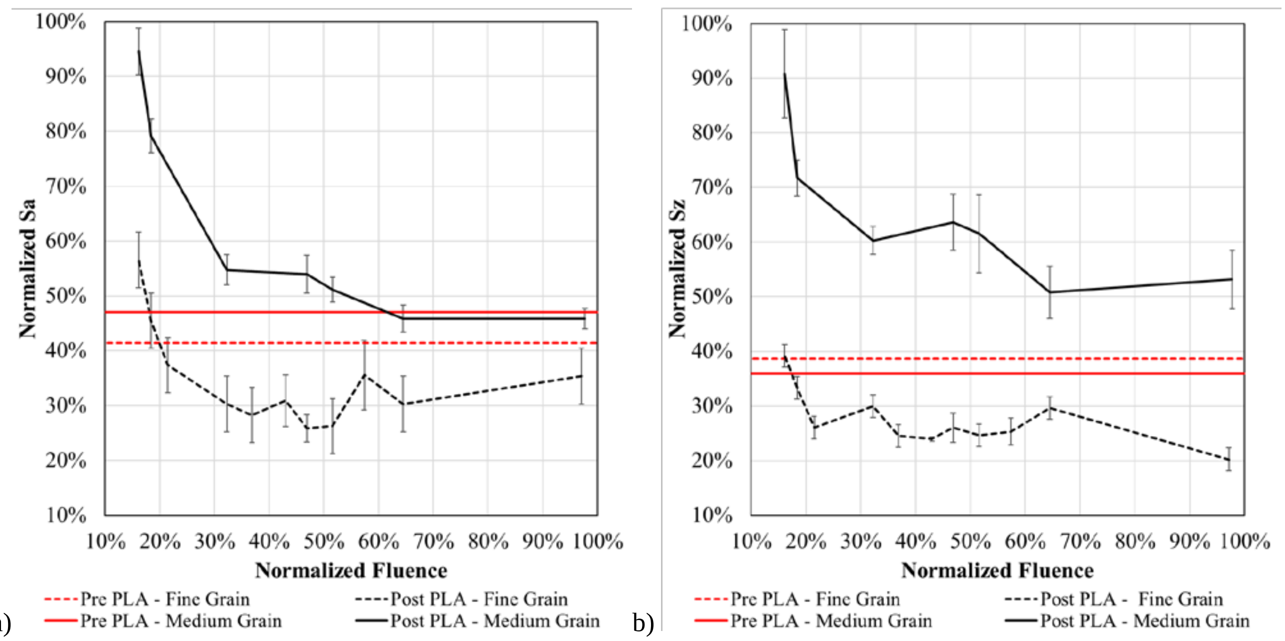


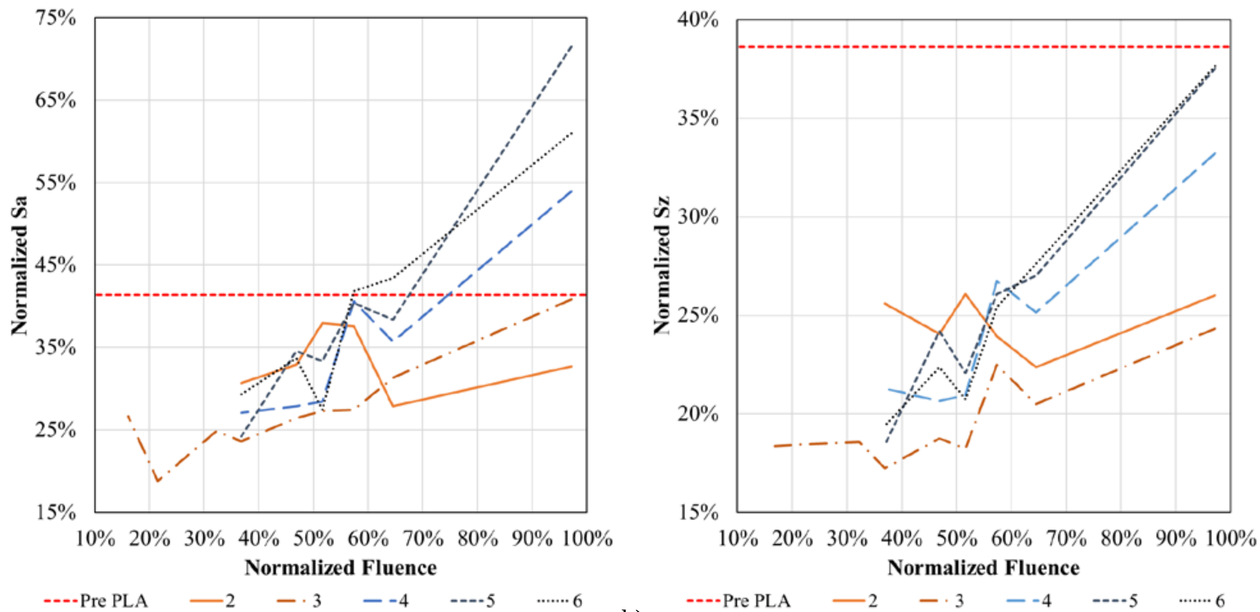
Figure 5. Variation of roughness Sa (a) and Sz (b) of two diamond grain surfaces in function of the fluence. The initial surface roughness pre-PLA is indicated.

3.3 Utilization of the burst mode

The pulse burst function is highly regarded as the enabling feature that can overcome some of the laser processing limitations: higher ablation rates and quality are achieved on metal samples due to its implementation in laser sources[12,13]. The surface roughness values Sa and Sz are displayed as a function of the pre-burst fluence (not intra burst) for 2 up to 6 bursts on fine grain surfaces (Figure 7) and coarse grain surfaces (Figure 7).

For fine diamond grain, the trend is clear for 3 bursts and more on both Figure 6a and Figure 6b: the roughness reduces when the fluence decreases. The lowest Sa and Sz values are captured for three bursts. Therefore, the experiments were pushed further at 3 bursts than any other number of bursts. Nevertheless, the trend would indicate that 5 bursts could achieve a lower roughness than achieved by 3 bursts below a fluence of 36%. Further testing is needed to confirm that 5 bursts processing performs better than 3 bursts in terms of surface quality. While the trend is clear for 3 up to 6 bursts, the results for 2 burst results are less clear, it appears that behavior is similar to single pulse processing.

Most importantly, as reported for metals, burst processing is better performing than single pulse processing on PCD material too. While the lowest Sa and Sz were respectively 26% and 24% (without counting Sz value for 100% fluence) after single pulse processing, the lowest Sa and Sz were respectively 19% and 17% after implementation of the burst. It corresponds to a reduction by a factor 2 of the initial roughness of the PCD wafer. In addition, the ablation rate with these parameters (3 bursts) is measured to be double that of the corresponding mechanical polishing rate.



a) b)

Figure 6. Variation of roughness Sa (a) and Sz (b) of a fine diamond grain surface with the fluence for six values of bursts. The initial surface roughness pre-PLA is indicated.

The trials with the burst function were repeated on a coarse diamond grain surface and the results are plotted in Figure 7. Although the trends between Figure 7a and Figure 7b are the same for the processing of fine diamond grain, for coarse diamond grain the trends between Figure 7a and Figure 7b are different. The Sa (Figure 7a) reduces for high values of fluence until reaching a limit. For any of the tested bursts (2 to 6), this limit does not go below the pre-PLA roughness of 44%. The Sz (Figure 7b) reaches a minimum for different values of fluence per tested burst. The minimum Sz achieved per burst only goes below the pre-PLA roughness by 2% maximum which lies within the error of the measurements. It cannot be concluded that burst function improves the surface quality on coarse grain diamond.

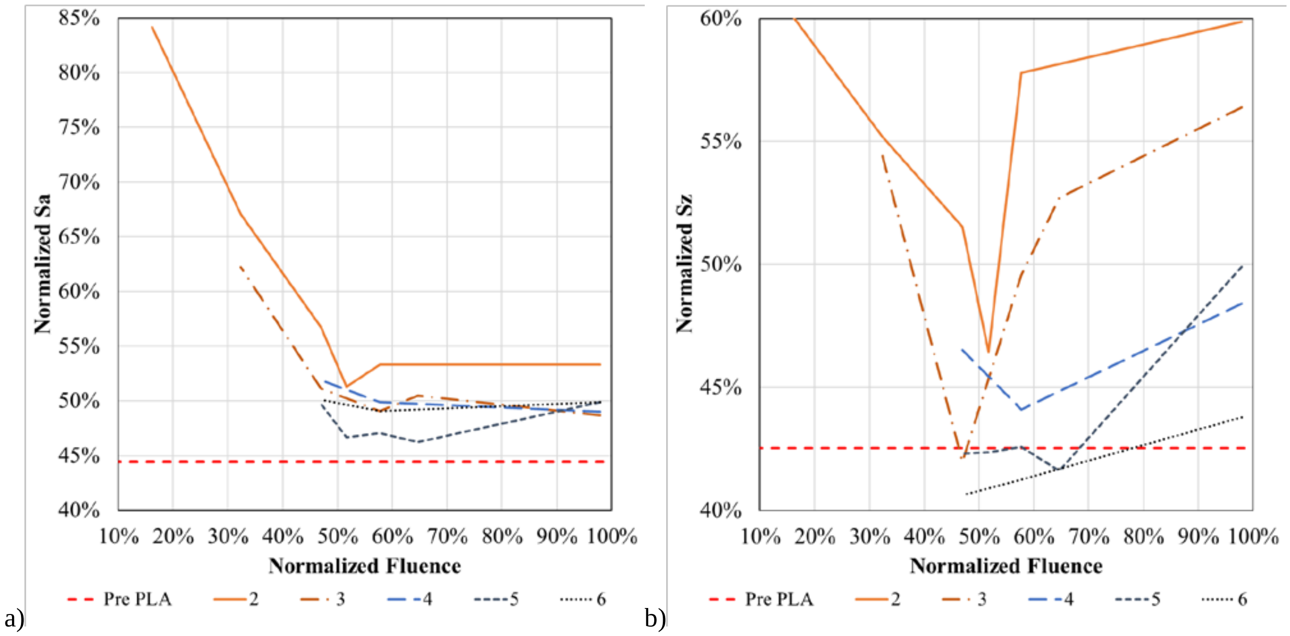
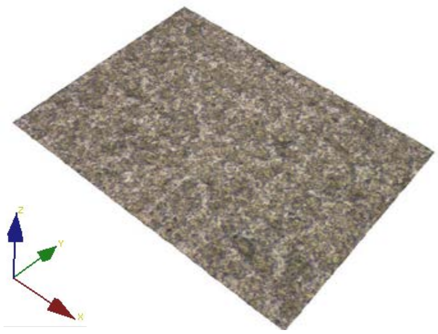
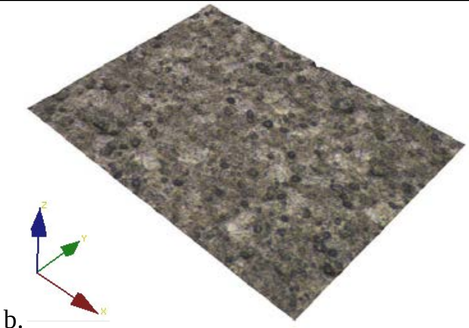
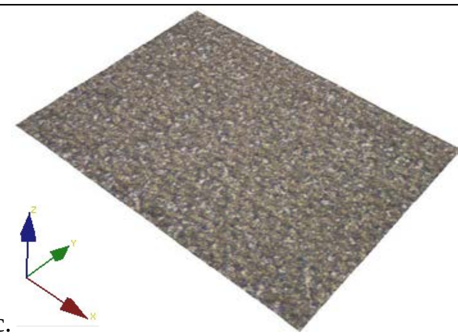
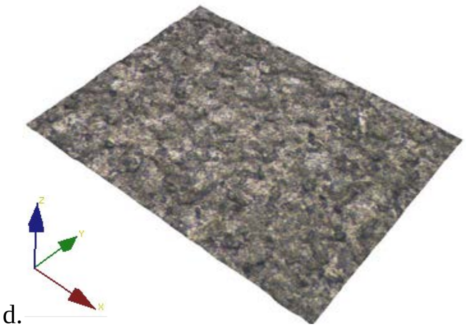
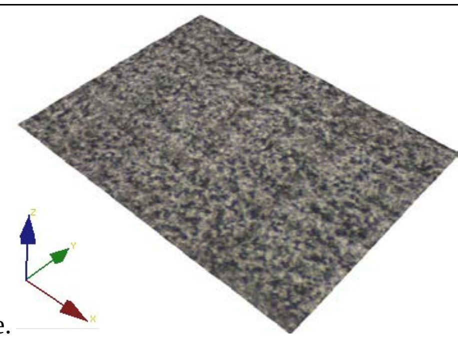
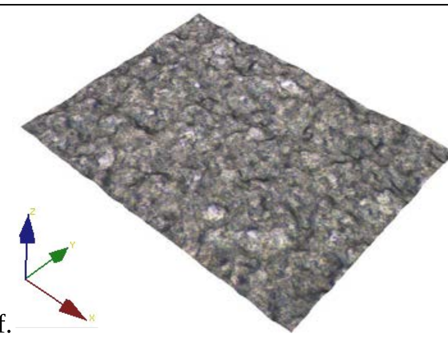


Figure 7. Variation of roughness Sa (a) and Sz (b) of a coarse diamond grain surface with the fluence for six values of bursts. The initial surface roughness pre-PLA surface is indicated.

Most of the investigations in literature about the advantages of burst mode processing are focused on the phenomena leading to an increase of the removal rate (incubation, plasma shielding and particle redeposition)[12,13]. Roughness reduction of metallic surfaces (copper and steel) is also possible after processing with pulse bursts. The incubation effects with pulse bursts can melt the metal which results in a flat shiny reflecting surface. This phenomenon is now demonstrated on PCD as well. For fine diamond, a very even and shiny surface can be achieved with 3 bursts (Table 4c). The improvement from single pulse processing is significant (Table 4a) and can be explained by the melting of the cobalt present at 20wt% within the PCD material (Table 1). This result is only achievable at low fluence as cavities are produced at high fluence instead (Table 4e). For coarse diamond, a minor reduction of the roughness is achievable by laser ablation. It is more important for single pulse processing at very high fluence: the surface is more even than the initial surface, but cavities remain on the surface (Table 4b). Burst processing at high fluence does not improve the surface quality neither at high fluence (Table 4d) nor at low fluence (Table 4f). First a higher fluence per pulse is required to process coarser diamond grain (Figure 5). Using the burst mode reduces the fluence of a pulse in a burst. Second the content of cobalt is lower by half in coarse diamond grain (10wt%), so there is less melting of cobalt than on fine diamond grain. Finally, single pulse processing at high fluence is the most effective to smoothly laser-ablate coarse diamond surfaces even though cavities are formed during the process.

Table 4. Microscopy images of laser-ablated surfaces.

	Fine diamond grain	Coarse diamond grain
Highest quality surface achieved with a single pulse	 a.	 b.
Highest quality surface achieved with a burst of 3 pulses	 c.	 d.
For fine diamond: surface achieved with high fluence burst of 3 pulses For coarse diamond: surface achieved with low fluence burst of 3 pulses	 e.	 f.

4. CONCLUSION

Even though an optical mirror polished surface is not obtained after laser processing a lapped diamond surface with a high-power femtosecond laser, some high performances are achieved on fine diamond grade: a reduction by two of the initial roughness is managed with an ablation rate double that of the removal rate of mechanical polishing. These performances are the outcome of an optimization of the laser processing parameters (number of passes and fluence) while limiting the heat accumulation effects (beam overlap) combined with the implementation of the burst function. The process could potentially be further optimized with the utilization of 5 bursts instead of 3. This optimization work also reveals the variation of results depending on the diamond grain size: processing coarser diamond grain is more challenging. Even after optimization of the laser/scanning parameters, single pulse processing at high fluence slightly improves the coarse diamond surface quality but the formation of cavities is observable, and the implementation of the burst function barely improves it. So no optimum parameter window exists to significantly reduce the roughness of coarse diamond by laser processing. Access to higher fluence via the use of higher power laser could confirm if the quality could be improved on coarse diamond grain surface. Further investigations are directed in utilizing ultrashort pulse laser with average power over 100W up to 1kW[14].

ACKNOWLEDGMENT

The authors would like to thank the European Union’s Horizon 2020 Research and Innovation Programme for funding this research, the company Element Six for funding this associated PhD research and providing PCD materials, and the company Class 4 Laser Professionals AG for allowing the use of their facilities and equipment.

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 687880.

REFERENCES

[1] Wilks J., Wilks E., “Properties and Applications of Diamond”, Butterworth-Heinemann, Oxford (1991)
[2] Chen Y., Zhang L., “Mechanical Polishing”, Polishing of Diamond Materials. Engineering Materials and Processes. Springer, London (2013)
[3] Kuriyagawa T., Syoji K., “High-efficiency Polishing of Polycrystalline Diamond”,. In: Seyfried P., Kunzmann H., McKeown P., Weck M. (eds) Progress in Precision Engineering. Springer, Berlin, Heidelberg (1991)
[4] Scalbert W., Tanner D., Laffir F., Holtz R., "Development of high-power laser ablation process for polycrystalline diamond polishing: Part 1. Fundamental understanding of PCD ultra-short pulsed laser ablation" Proc. SPIE 10525 (15 February 2018).
[5] Weber R., Graf T., Berger P., Onuseit V., Wiedenmann M., Freitag C., and Feuer A., “Heat accumulation during pulsed laser materials processing”, Optics Express, Vol. 22, No. 9 (5 May 2014)
[6] Weber R., Graf T., Freitag C., Feuer A., Kononenko T., and Konov V. I., “Processing constraints resulting from heat accumulation during pulsed and repetitive laser materials processing”, Optics express, Vol. 25, No. 4 (20 Feb 2017)
[7] Neuenschwander B., Jaeggi B., Schmid M., Hennig G., “Surface structuring with ultra-short laser pulses: Basics, limitations and needs for high throughput”, Physics Procedia 56, 1047 – 1058 (2014)
[8] Žemaitis A., Gečys P., Barkauskas M., Račiukaitis G.and Gedvilas M., “Highly-efficient laser ablation of copper by bursts of ultrashort tuneable (fs-ps) pulses”, Scientific Reports (2019)
[9] Sailera M., Bauerb F., Kleinera J., Kaisera M., “Scaling of Ablation Rates. Ablation Efficiency and Quality Aspects of Burst-Mode Micromachining of Metals”, Lasers in Manufacturing Conference (2015)
[10] Neuenschwander B., Jäggi B., Schmid M., Hunziker U., Luescher B., Nocera C., “Processing of industrially relevant non-metals with Laser pulses in the range between 10 ps and 50 ps”, Proc. ICALEO Paper M103 (2011).
[11] Neuenschwander B., Jäggi B., Schmid M., “From ps to fs: Dependence of the Material Removal Rate and the surface Quality on the Pulse Duration for Metals, Semiconductors and Oxides”, Physics Procedia 41, 794-801 (2013)
[12] Neuenschwander B., Kramer Th., Lauer B. and Jaeggi B., “Burst mode with ps- and fs-pulses: Influence on the removal rate, surface quality and heat accumulation”, Proc. of SPIE Vol. 9350 93500U-1 (2015)
[13] Metzner D., P. Lickschat, Weißmantel S., “Laser micromachining of silicon and cemented tungsten carbide using picosecond laser pulses in burst mode: ablation mechanisms and heat accumulation
[14] Saraceno, C.J., Sutter, D., Metzger, T. et al. “The amazing progress of high-power ultrafast thin-disk lasers”, J. Eur. Opt. Soc.-Rapid Publ. 15, 15 (2019).